

Targeting Multiple Management Objectives in Sustainable Fisheries

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Abstract

Modern fisheries management must balance between return (economic value) and risk (harvest uncertainty and stock collapse). Management tools should target multiple simultaneous management objectives. These include output, number of seasons, total stock value and its uncertain fluctuations. I provide a stylized fishery model for simulating the outcomes of these competing management objectives under various regulatory and market environments. Results show that these objectives need not be mutually exclusive. They can be traded off gradually, quantitatively and transparently. The trade-offs involve profit and output versus job provision, employment security, stock conservation and less-risky harvesting. The pursuit of higher return must balance against the risk of stock collapse and harvest fluctuations.

Keywords: marine reserve, fisheries management, simulations, trade-off.

1. Fisheries Management Objectives

Traditional fisheries management typically concerns the health of the fish stock, in particular, its size. For example, the Ecological Quality Objective (EcoQO) for the North Sea demersal fish community (Greenstreet et al., 2011) is the state-of-the-art development in this regard. It identifies size-based metrics as the most effective indicators of the state of the ecological community. Such metrics are also sensitive to environmental influence. The large fish indicator (LFI) is one such indicator that is sensitive to fishing-induced change. This complex relationship underscores the need for operational theoretical size-resolved multispecies fish community models to support management towards broader ecosystem objectives.

At the moment, quantitative fish stock assessment techniques are far in advance of successful fisheries management applications. For example, techniques such as stock synthesis (SS) (Methot Jr. & Wetzel, 2013) adopt a statistical age-structured population modeling framework. It is highly scalable from data-weak situations where it operates as an age-structured production model, to complex situations where it can flexibly incorporate multiple data sources and biological/environmental processes. Despite the advances in these techniques, there have been relatively few successful applications in management practice. Hilborn (2007) holds a more optimistic view. Besides using marine-protected areas as the central tool of a new approach to rebuilding the marine ecosystems of the world, he argues that much can also be learned from examples of successfully managed fisheries: "These lessons are stopping the competitive race to fish by appropriate incentives for fishing fleets and good governance. The major tool of resetting incentives is granting various forms of dedicated access, including community-based fishing rights, allocation to cooperatives, and individual fishing quotas. Many of the failed fisheries of the world occur in jurisdictions where central governments are not functional, and local control of fisheries is an essential part of the solution." (Hilborn, 2007, p. 296) The essential elements of these successfully managed fisheries are economic sustainability and the cooperative nature of the fishery industries. For example, BenDor et al. (2009) argue that this is particularly important in rural coastal areas where the fishing industry is often a dominant employer. They analyze the interactions between economic and ecological dynamic systems using a multi-agent dynamic model of fishery management. Multiple agents (fishers) harvest multiple fish species and adapt the amount and allocation of their effort to their value functions. These are given as net profits of the fish harvest sold for a market price. Their model suggests that competitive fisher behaviors lead to a decline of all fish stocks, as well as their profits. On the other hand, cooperative fisheries that jointly set sustainable limits for total harvest and effort can stabilize the fish stocks and profits at significantly higher levels. These then lead to a continuous accumulation of capital for all fishers.

I argue that, for modern fisheries managers, their first-and-foremost objectives must be to ensure that (1) the stock is sustainably harvested in a biological sense; (2) the stock is optimally harvested in an economic sense; and (3) all stakeholders are to be treated equally and fairly. For (1) and (2), the necessary hurdles must include a sustainable stock size, the total derivable economic value from the stock, and the periodic harvest output, effort and profit. For (3), the hurdles are less well-defined. However, it is reasonable to demand that they include the chances or probability of achieving the total derivable economic value; the number of harvest seasons required; and the variability of this random total derivable economic value. All of them affect to a large extent the livelihood of the parties employed by or involved in the fishery: fishermen, managers, scientists and coastal communities. Achieving these objectives often have the added bonus of ameliorating the economic consequences of a stock assessment error.

The economic value of the stock supports the fishermen, the crew, the community, the managers and the science. The variability or uncertainty of economic return affects those employed by the fishery. Workers have to be laid off in a low season, only to be hired back in a high season. Variability affects the stability of livelihood. Furthermore, the notion of maintaining a certain stock size is popular with various legislation (Lauck et al., 1998, p. S76). Thus, finding the probability that this could be achieved is important. In economics, we might similarly wish to maximize the probability of achieving certain levels of fishery economic value and the number of seasons required to achieve them. This is because they affect the long-term planning of the investment and construction of amenities and facilities in the community.

There are other non-economic but stock-related objectives. A complete list of these has been compiled by Novaczek (1995), Hockey and Branch (1997, p. 377) and Lauck et al. (1998, p. S77).

This paper attempts to target some common fisheries management objectives:

- (1) achieving sustained and optimal levels of periodic harvest effort, output and profit;
- (2) maximizing the total expected fish stock value; the probability of achieving this or certain pre-specified levels of total stock value; and the sustainable stock size;
- (3) minimizing the fluctuations in the total expected stock value; and the number of harvest periods to achieve the maximum total expected stock value.

I lay out the rest of the article as follows. The next section explains the model that runs simulations on the above management objectives. Section 3 then conducts a series of simulation experiments over these competing management objectives. I will highlight the inherent conflict and trade-off among these objectives. Section 4 concludes with policy implications.

2. The Simulation Model

My simulations are based on an erstwhile model (Li, 2000). There are two assumptions:

- (1) The fishery is cooperative, profit-maximizing, license-restricted, poaching-free, maintains a biologically sustained stock, and is mutually agreed to a legally binding division of harvest profits through a successfully negotiated internal transfer payment system (Munro 1996); and
- (2) Harvest costs and demand for the harvest output are governed by deterministic market conditions and there exists no uncertainty regarding stock size, harvestability, and market demand. The unit harvest effort cost and the perfectly competitive harvest output price are both constant.

Finally, the model also assumes a stable production function. The optimal harvest solution for the fleet is obtained by maximizing profit over harvest effort, subject to the harvest production equation and a stock sustainability requirement that links output to effort.

Next, a certain percentage of total harvestable area is designated as marine reserve or no-take zone where all commercial harvest activities are banned. Suppose the marine reserve is strictly monitored and enforced and that the stock distribution over the total harvestable area is perfectly homogeneous. A perfectly homogeneous stock distribution assumption implies that the percentage of biomass inside the reserve and the percentage of biomass in the harvestable area are to be maintained at all times. Thus the biomass density (kg/m^3) throughout the reserve and harvestable area is constant. Therefore, when the harvestable area is being exploited, there will be a net migration of individuals (biomass) out of the reserve into the harvestable area. Also, the percentage of the reserve stock foraging outside the reserve area is the same as that of non-reserve stock foraging inside the reserve area and exchange between the two over time is consistent. Consequently, harvest will be a function of non-reserve stock and the intensity of fishing effort only.

Suppose that a fish stock is never going to collapse, the total value that can be derived from the fishery is the sum

of all sustained future periodic harvest profits discounted to the present. When the future prospect of a stock collapse poses a relevant threat, the assumption of a long time frame is no longer valid. Moreover, the fishery value that can be derived from harvest profits will also depend on when the collapse is likely to occur, and the timing of the collapse should also involve the interaction of effort and population dynamics.

Once the stock experiences an unexpected collapse, it can never recover to an economically viable level for sustainable harvest. The model assumes that a marine reserve can mitigate such a collapse. The mathematics shows that the probability of stock collapse decreases with the proportion of the total harvestable area designated as a marine reserve.

My simulation model, based on Li (2000), is a multi-period, marine-reserve-adjusted, stochastic-stock-size Schaefer model. It examines the relationship between the risk of stock collapse and the return of fishery economic value by using optimum harvesting and a marine reserve as the twin tools of management control. Next, I run simulations on this model using a stylized fishery. My objective is to show that the reserve size and harvest effort can target some common management objectives, in addition to maximizing fishery economic value.

The main equations of the model are summarized in Appendix A (Li, 2000). My simulations are conducted by treating the model as an application package with the input parameters, control variables and output values detailed in the following Table 1.

Table 1. Input parameters, control variables and output values for the simulation model

Input parameters:		
Parameter name:	Symbol:	Unit:
1. intrinsic growth rate	r	%
2. per kg fish price	p	AUD\$/mmt
3. stock carrying capacity	k	mmt (million metric tons)
4. harvesting cost	c	AUD\$/worker boat hour
5. catchability coefficient	q	mmt per worker boat hour per unit biomass
6. discount rate	ρ	%
7. stock collapse rate	λ	probability
Control variables:		
Variable name:	Symbol:	Unit:
1. reserve feasibility ($s < 1 - c/pqk$)	$1 - c/pqk$	%
2. reserve size	s	%
3. optimal reserve size	$s^* = 1 - \left\{ \frac{3\lambda c + \sqrt{9\lambda^2 c^2 + 8c\rho\lambda pqk}}{2\lambda pqk} \right\}$	%
4. sustainable harvest effort	$E^s = \frac{r}{2q(1-s)} \left\{ 1 - \frac{c}{pqk(1-s)} \right\}$	worker boat hour (mbh)
Output values/ Management objectives:		
Objective name:	Symbol	Unit:
1. sustainable periodic harvest profit	$\Pi^s = \frac{rpk}{4} \left(1 - \frac{c}{pqk(1-s)} \right)^2$	AUD\$ million
2. total expected fish stock value	$E(V^s) = \frac{\Pi^s}{(\rho + (1-s)\lambda)}$ $E(V^s)^*$ is the maximum $E(V^s)$ achieved at s^*	AUD\$ million
3. sustainable harvest output	$H^s = \frac{rk}{4} \left\{ 1 - \left(\frac{c}{pqk(1-s)} \right)^2 \right\}$	mmt

4. sustainable stock size	$X_2^s = \frac{k}{2} \left\{ 1 + \frac{c}{pqk(1-s)} \right\}$	mmt
5. time (no. of seasons) to $E(V^s)$	$t = \frac{1}{\rho} \ln \left(\frac{\rho + (1-s)\lambda}{(1-s)\lambda} \right)$ t^* is the t that reaches $E(V^s)^*$	harvest periods t
6. prob. of time to $E(V^s)$	$P(t) = \left(\frac{(1-s)\lambda}{(1-s)\lambda + \rho} \right)^{\frac{(1-s)\lambda}{\rho}}$	probability
7. prob. achieving 50% $E(V^s)^*$	$P(50\%E(V^s)^*) = \left(\frac{\Pi^s - 50\%E(V^s)^*\rho}{\Pi^s} \right)^{\frac{(1-s)\lambda}{\rho}}$	probability
8. prob. achieving 75% $E(V^s)^*$	$P(75\%E(V^s)^*) = \left(\frac{\Pi^s - 75\%E(V^s)^*\rho}{\Pi^s} \right)^{\frac{(1-s)\lambda}{\rho}}$	probability
9. prob. achieving 100% $E(V^s)^*$	$P(E(V^s)^*) = P(t^*) = \left(\frac{\Pi^s - E(V^s)^*\rho}{\Pi^s} \right)^{\frac{(1-s)\lambda}{\rho}}$	probability
10. prob. achieving 125% $E(V^s)^*$	$P(125\%E(V^s)^*) = \left(\frac{\Pi^s - 125\%E(V^s)^*\rho}{\Pi^s} \right)^{\frac{(1-s)\lambda}{\rho}}$	probability
11. prob. achieving 150% $E(V^s)^*$	$P(150\%E(V^s)^*) = \left(\frac{\Pi^s - 150\%E(V^s)^*\rho}{\Pi^s} \right)^{\frac{(1-s)\lambda}{\rho}}$	probability

The model input parameters include the intrinsic growth rate r , per kg price p , stock carrying capacity k , per worker-boat-hour harvest cost c and the fleet's catchability coefficient q . These are all parameters in the original Schaefer model (1954). The market discount rate ρ and the Poisson stock discount rate λ are from Li's model. The first control variable is the marine reserve size s that is set by the regulators. There is a feasibility requirement on the s so that the model is implementable. That is, s must produce sensible (non-negative and finite) solutions for harvest output, effort and profit. The second control variable is harvest effort E , although its level is always set to maximize total harvest profit and the fishery's economic value. This is because fishers will fully exploit the regulations once they are laid down, whether the regulations are on quota, fishing area, limited season or gear used. In this paper we assume no irregular or illegal activities such as poaching. Consequently, s and E as control variables for targeting management objectives.

The model outputs represent various management objectives. Traditionally, they include the sustainable periodic harvest profit, harvest output, and the sustainable stock size. In this paper, I add the total expected stock value; the expected time (number of harvest periods) and the probability of achieving the total expected stock value; and the respective probabilities of achieving 50%, 75%, 100%, 125% or 150% of total expected stock value.

3. Simulation Results and Discussions

3.1 Simulating Maximum Stock Value by Comparative Statics

Simulation results of 8 different scenarios for a stylized fishery are summarized in Table 2. The 8 scenarios include the base scenario and 7 other scenarios. In each scenario exactly one parameter has a different value from the base scenario. In economic analysis, the technique is known as comparative statics. It measures the change in optimum values of the objective function and of the control variables when exactly one parameter of the model experiences a change. In the base scenario, the stock intrinsic growth rate r is 1% p.a., per kg fish price p is AUD\$10 (\$10 Australian dollars), the stock carrying capacity k is 1 million metric tons (or 1 mmt), the harvesting cost c is AUD\$50 per worker per boat per hour (including all food, fuel, bait and tackle, equipment hire, service and maintenance), the fleet's harvesting productivity (the catchability coefficient q) is 1×10^{-7} mmt per worker boat hour per mmt biomass. This implies that, for example, given a biomass k of 1 mmt, for each vessel or boat that operates for one hour, a crew of 10 fishermen can catch 1×10^{-6} mmt or 1 metric tonne of fish.

Finally, the financial-markets discount rate ρ is 5% p.a. and the natural rate of stock collapse λ (without a marine reserve) is 0.02 (i.e., every year the stock has a probability of 0.02 of collapsing). The reserve size s is defined as the percentage of biomass not subject to exploitation. This is equivalent to s being the percentage of marine waters fenced off under the homogeneous stock distribution assumption. Any feasible or workable reserve size

must be under 95% ($1-c/pqk$) and the calculated optimal reserve size s^* (that maximizes the total expected stock value) is 41.94%. This will achieve a seasonal harvest profit IT^s of AUD\$20.88 million (out of a sustained harvest output H^s of 0.002481 mmt and utilizing harvesting effort E^s of 78,702 worker-boat-hours each season). The superscripts $*$ and s imply the optimal and the sustainable, respectively. The maximum total expected stock value is $E(V^s)^*$ (the maximum $E(V^s)$ value) = AUD\$338.89 million. Following this harvesting program, an expected 33.377 harvest seasons (t^*) will pass before $E(V^s)^*$ is realized, with a probability of success, $P(E(V^s)^*)$, of 0.679. The probabilities of achieving 50% and 75% of $E(V^s)^*$, i.e., $P(0.5E(V^s)^*)$ and $P(0.75E(V^s)^*)$, are 0.886 and 0.804 respectively. It is not possible to achieve 125% and 150% of $E(V^s)^*$ ($P(1.25E(V^s)^*) = P(1.5E(V^s)^*) = 0$). Finally, the resulting sustained biomass X_2^s is 0.543 mmt (the lower sustained biomass $X_1^s = 0.457$ mmt will not be pursued by managers).

Table 2. Comparative statics on maximum total expected fish stock value

	Base scenario	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
				$q = 3 \times 10^{-7}$ mmt /mbh/mmt				
Management objectives:	Output values:	$p = \$15/\text{kg}$	$k = 2$ mmt	biomass	$r = 5\%$ p.a.	$c = \$100/\text{mbh}$	$\rho = 10\%$ p.a.	$\lambda = 0.1$
$1-c/pqk$	95.00%	96.67%	97.50%	98.33%	95.00%	90.00%	95.00%	95.00%
s^*	41.94%	53.87%	60.70%	68.52%	41.94%	12.72%	21.39%	68.92%
IT^s	\$20.879	\$32.276	\$43.842	\$22.423	\$104.397	\$19.600	\$21.921	\$17.604
$E(V^s)^*$	\$338.887	\$544.969	\$757.708	\$398.303	\$1,694.436	\$290.552	\$189.427	\$217.110
H^s	0.002481	0.002487	0.004980	0.002493	0.012407	0.002467	0.002490	0.002435
E^s	78,702	100,557	119,123	50,147	393,512	50,721	59,561	134,977
X_1^s	0.457	0.464	0.936	0.474	0.457	0.443	0.468	0.420
X_2^s	0.543	0.536	1.064	0.526	0.543	0.557	0.532	0.580
t^*	33.377	37.187	39.923	43.817	33.377	27.035	19.962	19.175
$P(t^*)$	0.679	0.710	0.731	0.759	0.679	0.624	0.731	0.551
$P(0.5E(V^s)^*)$	0.886	0.904	0.915	0.929	0.886	0.851	0.915	0.795
$P(0.75E(V^s)^*)$	0.804	0.831	0.849	0.871	0.804	0.753	0.849	0.680
$P(E(V^s)^*)$	0.679	0.710	0.731	0.759	0.679	0.624	0.731	0.551
$P(1.25E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	0.402	n/a	0.400
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.200

In scenario 2, p is raised to AUD\$15 per kg (keeping all other input parameters unchanged). The harvesting fleet still aims to maximize periodic harvest profit and total expected stock value by trading off this maximum periodic profit with the risk of sudden stock collapse. Compared to the base scenario, s^* is increased to 53.87% but still within the feasible limit of 96.67%. This will achieve a higher IT^s of AUD\$32.28 million (out of a higher H^s of 0.002487 mmt and utilizing higher E^s of 100,557 worker-boat-hours each season). $E(V^s)^*$ is higher as AUD\$544.97 million. In this scenario, more seasons ($t^* = 37.19$) are required to achieve $E(V^s)^*$ but the probability of success is also higher (0.710). The probabilities of achieving 50% and 75% of $E(V^s)^*$ are also higher at 0.904 and 0.831 respectively, compared to those in the based scenario. However, X_2^s is lower at 0.536 mmt despite (or indeed because of) the more alluring market price. Again it is impossible to achieve 125% or 150% of $E(V^s)^*$.

In scenario 3, k is raised to 2 mmt. s^* is increased to 60.70% but within the new feasibility limit of 97.50%. This will achieve a higher IT^s of AUD\$43.84 million (out of a higher H^s of 0.00498 mmt and utilizing higher E^s of 119,123 worker-boat-hours each season). $E(V^s)^*$ is higher at AUD\$757.71 million. Still more seasons ($t^* = 39.92$) are required to achieve $E(V^s)^*$ but the probability of success is also increased to 0.731. The probabilities of achieving 50% and 75% of $E(V^s)^*$ are also correspondingly higher at 0.915 and 0.849 respectively. With a higher

biomass k to start with, the resulting sustainable stock size of X_2^s is also higher at 1.0636 mmt.

In scenario 4, q is raised to 3×10^{-7} . All other input parameters remain unchanged from the base scenario, to which all comparisons are again made. s^* is increased to 68.52% and is within the now more tolerable feasibility limit of 98.33%. This will achieve a higher IT^s of AUD\$22.42 million (out of a higher H^s of 0.00249 mmt and utilizing lower E^s of 50,147.31 worker-boat-hours each season). Again, $E(V^s)^*$ is higher at AUD\$398.30 million. The probability of success at achieving $E(V^s)^*$ is higher at 0.759. On the other hand, more seasons ($t^* = 43.82$) are also required to achieve this. Correspondingly, the probabilities of successfully achieving 50% and 75% of $E(V^s)^*$ are higher at 0.929 and 0.871 respectively. With a higher catch efficiency, the sustainably harvested stock size of X_2^s is not surprisingly lower at 0.526 mmt.

In the 5th scenario, the stock growth rate r is increased to 5%. The optimal reserve size s^* stays at 41.94% and within the same feasibility limit of 95%. This will achieve a significantly higher seasonal harvest profit IT^s of AUD\$104.40 million (out of a much higher H^s of 0.01241 mmt and utilizing an equally impressive higher E^s of 393,511.52 worker-boat-hours each season). The total expected stock value $E(V^s)^*$ has increased to AUD\$1,694.44 million. This suggests that a higher stock growth rate brings in substantially more economic benefits than a rise in market price, biomass or catch efficiency. What's more, all relevant probabilities of success, number of seasons required and the sustainably harvested stock size are steady.

In the 6th scenario, c is more costly at AUD\$100 per worker per boat per hour. s^* is dramatically lowered to 12.72% but still within the now lower feasibility limit of 90%. IT^s , H^s , E^s , $E(V^s)^*$ also dropped significantly to AUD\$19.60 million, 0.002467 mmt, 50,721.21 worker-boat-hours, and AUD\$290.55 million respectively. This suggests a higher harvesting cost (perhaps due to shortage of skilled fishermen, higher wages and/or expensive capital equipment) could be devastating to the fishing community. The probabilities of successfully achieving $E(V^s)^*$ or 50%, 75% or 125% of it are also lower to 0.624, 0.851, 0.753 and 0.402 respectively. The only bright spot is that fewer seasons ($t^* = 27.04$) are required to achieve $E(V^s)^*$ and the sustained stock size X_2^s is higher at 0.557 mmt.

In the 7th scenario, ρ is raised to 10% p.a. (perhaps during a recession). The effect of raising interest rate (or discount rate) is to slow down the economy, reducing investment, employment and consumption. The reason for the economy slowing down is that future earnings are discounted more (meaning less valuable compared to current earnings). Current borrowing costs are also higher and these ultimately reduce economic activity, including fishery. To make up for the lower future harvest profits, the stock is harvested more intensively. This leads to a lower optimal reserve size s^* at 21.39% (within the same feasible boundary of 95%). As a result of the more intensive use of the resource, IT^s and H^s are higher at AUD\$21.92 million and 0.00249 mmt respectively. However, harvest effort E^s is lower at 59,561.42 worker-boat-hours each season, reflecting a slowing economy. High interest rates eat into the total expected stock value $E(V^s)^*$, which dropped to AUD\$189.43 million. The lower $E(V^s)^*$ requires fewer seasons ($t^* = 19.96$) to achieve. The probabilities of success at achieving 50%, 75% and 100% of $E(V^s)^*$ are respectively higher at 0.915, 0.849 and 0.731. Not surprisingly, the more intensive use of the stock lowered the sustainably harvested stock size X_2^s to 0.532 mmt.

In the last scenario 8, λ is raised to 0.1. This means catastrophic stock collapse (making all future harvests non-profitable) is now five times more likely than the base scenario. It is not surprising that a marine reserve is now more appealing as an insurance against stock collapse and s^* is increased to 68.92% (within the same feasibility limit of 95%). A higher reserve size eats into the harvest profit IT^s and output H^s , which are both lower at AUD\$17.60 million and 0.00244 mmt respectively. As a result, fishermen need to work harder at a higher E^s of 134,976.96 worker-boat-hours each season. The result is a lower $E(V^s)^*$ of AUD\$217.11 million. They now require only $t^* = 19.18$ seasons to achieve but with a lower probability of success at 0.551. The probabilities of

success at achieving 50%, 75%, 125% and 150% of $E(V^s)^*$ are all lower at 0.795, 0.680, 0.440 and 0.200 respectively. The latter two are only possible (probability > 0) with a lower $E(V^s)$ to begin with. Stronger protection measure (higher s^*) means that X_2^s is also now higher at 0.580 mmt, vis-à-vis the base scenario.

3.2 Simulating Competing Management Objectives

In the next set of simulations, the previous eight scenarios are retained. However, I do not maximize the total expected stock value by selecting the optimal marine reserve size and harvest effort. Instead, I simulate the output values of competing management objectives by running the reserve size over its entire feasible range in each scenario (Tables 3 to 10). Unlike the reserve size, harvest effort cannot be manipulated in this manner. This is because fishers always fully exploit the regulatory environment. Therefore any less-than-optimal harvest effort will not be realistic.

Table 3. Simulating competing management objectives for base scenario

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	95.00%
Π^s	\$22.563	\$22.299	\$21.973	\$21.556	\$21.007	\$20.250	\$19.141	\$17.361	\$14.063	\$6.250	\$0.000
$E(V^s)^*$	\$322.321	\$327.932	\$332.919	\$336.814	\$338.822	\$337.500	\$330.011	\$310.020	\$260.417	\$120.192	\$0.000
H^s	0.002494	0.002492	0.002490	0.002487	0.002483	0.002475	0.002461	0.002431	0.002344	0.001875	0.000000
E^s	47,500	52,469	58,594	66,327	76,389	90,000	109,375	138,889	187,500	250,000	0
X_1^s	0.475	0.472	0.469	0.464	0.458	0.450	0.438	0.417	0.375	0.250	0.000
X_2^s	0.525	0.528	0.531	0.536	0.542	0.550	0.563	0.583	0.625	0.750	1.000
t	25.055	26.583	28.341	30.397	32.845	35.835	39.620	44.672	52.054	65.162	78.637
$P(t)$	0.606	0.620	0.635	0.653	0.674	0.699	0.728	0.765	0.812	0.878	0.924
$P(0.5E(V^s)^*)$	0.828	0.842	0.856	0.870	0.883	0.897	0.911	0.923	0.929	n/a	n/a
$P(0.75E(V^s)^*)$	0.718	0.738	0.759	0.779	0.800	0.821	0.840	0.854	0.829	n/a	n/a
$P(E(V^s)^*)$	0.573	0.598	0.624	0.649	0.674	0.696	0.707	0.639	n/a	n/a	n/a
$P(1.25E(V^s)^*)$	0.327	0.341	0.345	0.322	n/a	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 4. Simulating competing management objectives for scenario 2

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	96.67%
Π^s	\$35.042	\$34.774	\$34.440	\$34.014	\$33.449	\$32.667	\$31.510	\$29.630	\$26.042	\$16.667	\$0.000
$E(V^s)^*$	\$500.595	\$511.377	\$521.820	\$531.463	\$539.501	\$544.444	\$543.283	\$529.101	\$482.253	\$320.513	\$0.000
H^s	0.002497	0.002497	0.002496	0.002494	0.002492	0.002489	0.002483	0.002469	0.002431	0.002222	0.000000
E^s	48,333	53,498	59,896	68,027	78,704	93,333	114,583	148,148	208,333	333,333	(0)
X_1^s	0.483	0.481	0.479	0.476	0.472	0.467	0.458	0.444	0.417	0.333	(0.000)
X_2^s	0.517	0.519	0.521	0.524	0.528	0.533	0.542	0.556	0.583	0.667	1.000
T	25.055	26.583	28.341	30.397	32.845	35.835	39.620	44.672	52.054	65.162	86.615
$P(t)$	0.606	0.620	0.635	0.653	0.674	0.699	0.728	0.765	0.812	0.878	0.944
$P(0.5E(V^s)^*)$	0.821	0.836	0.851	0.867	0.882	0.898	0.913	0.929	0.942	0.934	n/a
$P(0.75E(V^s)^*)$	0.705	0.727	0.750	0.773	0.797	0.822	0.846	0.869	0.884	n/a	n/a
$P(E(V^s)^*)$	0.548	0.576	0.606	0.636	0.667	0.698	0.726	0.739	n/a	n/a	n/a
$P(1.25E(V^s)^*)$	0.239	0.247	0.236	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 5. Simulating competing management objectives for scenario 3

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	97.50%
Π^s	\$47.531	\$47.261	\$46.924	\$46.492	\$45.920	\$45.125	\$43.945	\$42.014	\$38.281	\$28.125	\$0.000
$E(V^s)^*$	\$679.018	\$695.012	\$710.967	\$726.443	\$740.647	\$752.083	\$757.678	\$750.248	\$708.912	\$540.865	\$0.000
H^s	0.004997	0.004996	0.004995	0.004994	0.004991	0.004988	0.004980	0.004965	0.004922	0.004688	0.000000
E^s	48,750	54,012	60,547	68,878	79,861	95,000	117,188	152,778	218,750	375,000	0
X_1^s	0.975	0.972	0.969	0.964	0.958	0.950	0.938	0.917	0.875	0.750	0.000
X_2^s	1.025	1.028	1.031	1.036	1.042	1.050	1.063	1.083	1.125	1.250	2.000
T	25.055	26.583	28.341	30.397	32.845	35.835	39.620	44.672	52.054	65.162	92.302
$P(t)$	0.606	0.620	0.635	0.653	0.674	0.699	0.728	0.765	0.812	0.878	0.955
$P(0.5E(V^s)^*)$	0.816	0.832	0.848	0.864	0.880	0.897	0.914	0.931	0.947	0.956	n/a
$P(0.75E(V^s)^*)$	0.695	0.718	0.743	0.768	0.793	0.820	0.847	0.873	0.897	n/a	n/a
$P(E(V^s)^*)$	0.528	0.559	0.590	0.624	0.658	0.694	0.728	0.757	0.694	n/a	n/a
$P(1.25E(V^s)^*)$	0.106	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 6. Simulating competing management objectives for scenario 4

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	98.33%
Π^s	\$24.174	\$24.083	\$23.969	\$23.824	\$23.630	\$23.361	\$22.960	\$22.299	\$21.007	\$17.361	\$0.000
$E(V^s)^*$	\$345.337	\$354.157	\$363.169	\$372.245	\$381.136	\$389.352	\$395.863	\$398.203	\$389.017	\$333.868	\$0.000
H^s	0.002499	0.002499	0.002499	0.002499	0.002498	0.002497	0.002496	0.002492	0.002483	0.002431	0.000000
E^s	16,389	18,176	20,399	23,243	27,006	32,222	39,931	52,469	76,389	138,889	0
X_1^s	0.492	0.491	0.490	0.488	0.486	0.483	0.479	0.472	0.458	0.417	0.000
X_2^s	0.508	0.509	0.510	0.512	0.514	0.517	0.521	0.528	0.542	0.583	1.000
t	25.055	26.583	28.341	30.397	32.845	35.835	39.620	44.672	52.054	65.162	100.346
$P(t)$	0.606	0.620	0.635	0.653	0.674	0.699	0.728	0.765	0.812	0.878	0.967
$P(0.5E(V^s)^*)$	0.809	0.825	0.842	0.859	0.877	0.895	0.913	0.931	0.950	0.966	n/a
$P(0.75E(V^s)^*)$	0.681	0.706	0.732	0.759	0.787	0.815	0.845	0.875	0.905	0.924	n/a
$P(E(V^s)^*)$	0.499	0.532	0.566	0.603	0.641	0.682	0.724	0.765	0.789	n/a	n/a
$P(1.25E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 7. Simulating competing management objectives for scenario 5

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	95.00%
Π^s	\$112.813	\$111.497	\$109.863	\$107.781	\$105.035	\$101.250	\$95.703	\$86.806	\$70.313	\$31.250	\$0.000
$E(V^s)^*$	\$1,611.607	\$1,639.660	\$1,664.595	\$1,684.072	\$1,694.108	\$1,687.500	\$1,650.054	\$1,550.099	\$1,302.083	\$600.962	\$0.000
H^s	0.012469	0.012461	0.012451	0.012436	0.012413	0.012375	0.012305	0.012153	0.011719	0.009375	0.000000
E^s	237,500	262,346	292,969	331,633	381,944	450,000	546,875	694,444	937,500	1,250,000	0
X_1^s	0.475	0.472	0.469	0.464	0.458	0.450	0.438	0.417	0.375	0.250	0.000
X_2^s	0.525	0.528	0.531	0.536	0.542	0.550	0.563	0.583	0.625	0.750	1.000
t	25.055	26.583	28.341	30.397	32.845	35.835	39.620	44.672	52.054	65.162	78.637
$P(t)$	0.606	0.620	0.635	0.653	0.674	0.699	0.728	0.765	0.812	0.878	0.924
$P(0.5E(V^s)^*)$	0.828	0.842	0.856	0.870	0.883	0.897	0.911	0.923	0.929	n/a	n/a
$P(0.75E(V^s)^*)$	0.718	0.738	0.759	0.779	0.800	0.821	0.840	0.854	0.829	n/a	n/a
$P(E(V^s)^*)$	0.573	0.598	0.624	0.649	0.674	0.696	0.707	0.639	n/a	n/a	n/a
$P(1.25E(V^s)^*)$	0.327	0.341	0.345	0.322	n/a	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 8. Simulating competing management objectives for scenario 6

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%
Π^s	\$20.250	\$19.753	\$19.141	\$18.367	\$17.361	\$16.000	\$14.063	\$11.111	\$6.250	\$0.000
$E(V^s)^*$	\$289.286	\$290.487	\$290.009	\$286.990	\$280.018	\$266.667	\$242.457	\$198.413	\$115.741	\$0.000
H^s	0.002475	0.002469	0.002461	0.002449	0.002431	0.002400	0.002344	0.002222	0.001875	0.000000
E^s	45,000	49,383	54,688	61,224	69,444	80,000	93,750	111,111	125,000	0
X_1^s	0.450	0.444	0.438	0.429	0.417	0.400	0.375	0.333	0.250	0.000
X_2^s	0.550	0.556	0.563	0.571	0.583	0.600	0.625	0.667	0.750	1.000
t	25.055	26.583	28.341	30.397	32.845	35.835	39.620	44.672	52.054	65.162
$P(t)$	0.606	0.620	0.635	0.653	0.674	0.699	0.728	0.765	0.812	0.878
$P(0.5E(V^s)^*)$	0.837	0.848	0.858	0.869	0.878	0.886	0.890	0.880	n/a	n/a
$P(0.75E(V^s)^*)$	0.734	0.749	0.764	0.777	0.789	0.796	0.788	0.623	n/a	n/a
$P(E(V^s)^*)$	0.603	0.620	0.634	0.645	0.647	0.621	n/a	n/a	n/a	n/a
$P(1.25E(V^s)^*)$	0.403	0.404	0.386	0.285	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 9. Simulating competing management objectives for scenario 7

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	95.00%
Π^s	\$22.563	\$22.299	\$21.973	\$21.556	\$21.007	\$20.250	\$19.141	\$17.361	\$14.063	\$6.250	\$0.000
$E(V^s)^*$	\$188.021	\$188.978	\$189.419	\$189.089	\$187.562	\$184.091	\$177.228	\$163.784	\$135.216	\$61.275	\$0.000
H^s	0.002494	0.002492	0.002490	0.002487	0.002483	0.002475	0.002461	0.002431	0.002344	0.001875	0.000000
E^s	47,500	52,469	58,594	66,327	76,389	90,000	109,375	138,889	187,500	250,000	0
X_1^s	0.475	0.472	0.469	0.464	0.458	0.450	0.438	0.417	0.375	0.250	0.000
X_2^s	0.525	0.528	0.531	0.536	0.542	0.550	0.563	0.583	0.625	0.750	1.000
t	17.918	18.803	19.810	20.971	22.336	23.979	26.027	28.717	32.581	39.318	46.151
$P(t)$	0.699	0.713	0.728	0.746	0.765	0.787	0.812	0.842	0.878	0.924	0.955
$P(0.5E(V^s)^*)$	0.897	0.905	0.914	0.922	0.931	0.939	0.947	0.954	0.956	n/a	n/a
$P(0.75E(V^s)^*)$	0.820	0.833	0.847	0.860	0.873	0.886	0.897	0.903	n/a	n/a	n/a
$P(E(V^s)^*)$	0.694	0.711	0.728	0.744	0.757	0.760	0.694	n/a	n/a	n/a	n/a
$P(1.25E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
$P(1.5E(V^s)^*)$	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 10. Simulating competing management objectives for scenario 8

Management objectives/ Reserve size	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	95.00%
Π^s	\$22.563	\$22.299	\$21.973	\$21.556	\$21.007	\$20.250	\$19.141	\$17.361	\$14.063	\$6.250	\$0.000
$E(V^s)^*$	\$150.417	\$159.281	\$169.020	\$179.634	\$190.972	\$202.500	\$212.674	\$217.014	\$200.893	\$104.167	\$0.000
H^s	0.002494	0.002492	0.002490	0.002487	0.002483	0.002475	0.002461	0.002431	0.002344	0.001875	0.000000
E^s	47,500	52,469	58,594	66,327	76,389	90,000	109,375	138,889	187,500	250,000	0
X_1^s	0.475	0.472	0.469	0.464	0.458	0.450	0.438	0.417	0.375	0.250	0.000
X_2^s	0.525	0.528	0.531	0.536	0.542	0.550	0.563	0.583	0.625	0.750	1.000
t	8.109	8.837	9.710	10.780	12.123	13.863	16.219	19.617	25.055	35.835	47.958
$P(t)$	0.444	0.451	0.460	0.470	0.483	0.500	0.523	0.555	0.606	0.699	0.787
$P(0.5E(V^s)^*)$	0.577	0.605	0.635	0.666	0.699	0.732	0.766	0.799	0.823	0.667	n/a
$P(0.75E(V^s)^*)$	0.409	0.441	0.477	0.515	0.555	0.598	0.642	0.684	0.708	n/a	n/a
$P(E(V^s)^*)$	0.269	0.301	0.336	0.375	0.418	0.464	0.512	0.555	0.554	n/a	n/a
$P(1.25E(V^s)^*)$	0.159	0.185	0.215	0.249	0.288	0.330	0.373	0.401	0.262	n/a	n/a
$P(1.5E(V^s)^*)$	0.077	0.095	0.115	0.139	0.167	0.196	0.218	0.189	n/a	n/a	n/a

The feasible limit (the last column of each table) for the reserve size is the largest acceptable percentage of the biomass (or surface area of the fishing ground if the stock is sufficiently mobile) beyond which seasonal harvest output, effort and profit will become negative. In all eight scenarios, the smaller the reserve size s (going from right to left along the tables), the higher the seasonal profit IT^s and seasonal output H^s . On the contrary, the following are lower: seasonal effort E^s ; sustainably harvested stock size X_2^s ; number of seasons required (t , not t^*) to achieved the expected total stock value $E(V^s)$ (not the maximum $E(V^s)^*$ achievable at the optimal s^*); and the probabilities of success at achieving the total expected stock value or any portion of it. In other words, under any regulatory environment (represented here by s), profit (IT^s) and output (H^s) are in conflict with and must be traded off for job provision and long-term employment security (E^s and t), stock conservation (X_2^s) and less risky harvesting ($P(E(V^s))$). More importantly, the trade-off is not a nuclear option (all or nothing). It can be done incrementally and evaluated quantitatively.

The probabilities of success at achieving 50%, 75%, 100%, 125% and 150% of the maximum total expected stock value $E(V^s)^*$ (not the $E(V^s)$ under each simulated s) appear to drop a little after reaching their maximum before becoming impossible to achieve (beyond the feasibility limit for s). The reason is that as the reserve size increases and reaches its feasibility limit ($1-c/pqk$), the seasonal harvest effort, output and profit and the total expected stock value drop abruptly. The rate of decline is much steeper than the rate of increase when the reserve size rises from zero. This decline in $E(V^s)$ is sufficiently large to overcome the reduction in the risk of stock collapse at high s , causing the probability of success at achieving $E(V^s)$ to drop slightly. Notice that the probability of achieving the maximum total expected stock value $E(V^s)^*$ at the optimal (most efficient) reserve size s^* is $P(E(V^s)^*)$ or $P(t^*)$. It is not the same as the probability of achieving the total expected stock value $E(V^s)$ at any other reserve size s , i.e., $P(E(V^s))$ or $P(t)$. The reason is that the most efficient seasonal output, effort and profit under the optimum-harvesting regime are different for different reserve size. This will lead to a different total expected stock value, i.e., all discounted future harvest profits calculated at present.

Finally, at the reserve size's feasibility limit, all seasonal harvest effort, output and profit go to zero so there will be no total expected stock value to speak of. The probability of success becomes meaningless. Without harvesting, the biomass reaches its biological maximum carrying capacity (X_2^s). Notice that X_1^s and X_2^s are both achievable and sustainable levels of the biomass. Since $X_2^s > X_1^s$, managers will always strive to achieve X_2^s .

4. Policy Implications

Modern fisheries management should be objective-oriented and follow a partnership approach. Any committee of fishers, managers and community members must not see their differing and competing objectives as conflicting goals that can only be either one or the other (mutually exclusive). Instead, their desires or agendas must be laid bare to all concerned and subject to benign negotiations and agreeable trade-offs. Furthermore, the trade-offs should be done gradually (i.e., no objectives should be 0% or 100% satisfied) and be quantitatively transparent.

In this paper, I adopted a multi-period, marine-reserve-adjusted, and random-stock-collapse-prone modification of the original Schaefer model (Li, 2000). I then ran simulations on various common management objectives. The simulations were run on the principle of optimum harvesting (i.e., restricted entry and profit maximization). This uses the reserve size and fishing effort to balance the return (total derivable stock value) against risks (of random stock collapse and uncertainty in total derivable stock value).

The simulation results are two-fold. First, by maximizing total stock value, changes in the model parameters can drastically affect the outcomes of the common objectives. For example, a higher stock growth rate brings in substantially more economic benefits than a rise in market price, biomass or catch efficiency; whereas a higher harvesting cost could be devastating to the fishing community. Rising interest rates force the harvest fleet to work harder by both cutting harvest effort and fishing more intensively into the stock. Higher collapse risks bring about the exact opposite.

Second, by altering the regulatory environment (represented by the reserve size), I have shown that profit and output are in conflict with and must be traded off the following: job provision and long-term employment security, stock conservation and less risky harvesting. More importantly, the trade-off can be achieved gradually and

incrementally. It is not merely either one or the other. It can also be quantitatively evaluated. An economically viable harvest return must balance against the risk of stock collapse and harvest uncertainty.

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